The Cross-Spectra of Cir X−1: Evolution of Time Lags

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ABSTRACT

Earlier work showed that the track in the X-ray hardness-intensity diagram of Cir X-1 corresponds to a Z track in its color-color diagram. In this paper, we study the cross spectrum of Cir X-1 in different regions of the hardness-intensity diagram with $RXTE$/PCA data. Comparing the light curves of Cir X-1 for the energy band 1.8-5.1 keV to those for 5.1-13.1 keV, we find that Cir X-1 exhibits a hard time lag on the horizontal branch, and a soft time lag on both the normal and the flaring branch. This indicates that Cir X-1 is similar to GX 5-1 and Cyg X-2 on the horizontal branch, but is different from them on the normal branch. We briefly discuss the mechanism of the time lags in the context of Comptonization models.

Subject headings: binaries: general — stars: individual (Cir X-1) — X-rays: stars

1. Introduction

X-ray spectral and fast-timing properties show that neutron star low-mass X-ray binaries (LMXBs) can be classified as Z sources or atoll sources (Hasinger & van der Klis 1989). For a typical Z source, the characteristic pattern in the X-ray color-color diagram is a Z-shaped track (hereafter Z track). The three limbs of the Z track are called the horizontal (HB), normal (NB), and flaring branch (FB), respectively. The transition region between the HB and the NB and that between the NB and the FB are called the apex (hard apex) and the anapex (soft apex), respectively. The timing properties of a LMXB, e.g. the characteristics of the Fourier power density spectra, are strongly correlated with their position in the Z track (see the review by van der Klis 1995; Hasinger & van der Klis 1989).

The Fourier cross spectrum has been used to study the frequency dependence of the relative time lags between the intensity variations in different energy bands. Van der Klis et al. (1987) first used this technique to study the HB and the NB of Cyg X-2 and GX 5-1. They have found that the time lag of low frequency noise (LFN) is complex. A soft lag, i.e., the observed soft photons lag the observed hard photons, exists below a frequency of a few hertz on the HB. Vaughan et

al. (1994) studied the intensity variations of GX 5-1 on its HB and found that at low frequencies the X-ray intensity variations at low energies lag those at higher energies by tens of milliseconds. Hard time lags have been observed in Horizontal-Branch quasi-periodic Oscillations (HBOs) and Normal-Branch quasi-periodic Oscillations (NBOs) in GX 5-1 (van der Klis et al. 1987; Vaughan et al. 1994; Vaughan et al. 1999) and in Cyg X-2 (van der Klis et al. 1987; Mitsuda & Dotani 1989), and HBOs and Flaring-Branch quasi-periodic Oscillations (FBOs) in Sco X-1 (Dieters et al. 2000).

Shirey et al. (Shirey 1998a; Shirey et al. 1998b; Shirey, Bradt, & Levine 1999) studied Cir X-1 during its transition to an active state with the Rossi X-ray Timing Explorer ($RXTE$) in 1997 June. They investigated the hardness intensity diagram (HID) of Cir X-1 and demonstrated that the spectral branches in the HID can be identified based on the timing properties as the horizontal, normal, and flaring branches of a Z source, respectively.

This paper uses the cross spectrum technique to measure the time lags in Cir X-1 and is organized as follows. The observations and the analysis are described in Section 2, while the results are reported in Section 3. Our discussions and conclusions are presented in Section 4.

2. The Observations and the Analysis Method

The $RXTE$ observations of Cir X-1 lasted 10 days from 1997 June 10 to June 20. Based on these observations, Shirey et al. (Shirey 1998a; Shirey et al. 1998b; Shirey, Bradt, & Levine 1999) studied the spectral and timing properties of Cir X-1 and identified it as a Z source. The observations of Cir X-1 on June 13 exhibited a complete track in its HID, and these are the data we use to study the cross spectra of Cir X-1. The data were obtained with the Proportional Counter Array (PCA). During the observations, one of the 5 Proportional Counter Units (PCUs) was sometimes off. For consistency, we extract data from the same four PCUs which were on. We only use *standard 2* and *single bit* modes. The *standard 2* data has 128 channels with 16 s time resolution, while the *single bit* data covers two energy bands, namely 1.8 keV - 5.1 keV (channel 0-13) and 5.1 keV - 13.1 keV (channel 14-35), with 122 μs (2^{-13} s) time resolution.

We use the *standard 2* data to make a HID for Cir X-1. Following previous studies (Shirey 1998a; Shirey et al. 1998b; Shirey, Bradt, & Levine 1999), we construct the HID from the background subtracted light curves in three energy channels, namely 1.8-6.5 keV (channel 0-17), 6.5 keV-13.1 keV (channel 14-35), and 13.1-18.6 keV (channel 36-50). The result is showed in Fig. 1. To investigate the timing properties of Cir X-1 along the Z track, we divide the HID into a number of boxes (see Fig. 1) and each box includes more than 1200 s data.

We use the *single bit* data to compute power density spectra (PDSs) and cross spectra of Cir X-1. The data are first divided into 16 s segments with 4 ms time resolution and the PDSs are computed for each segment. Then the PDSs from all the segments are averaged and logarithmically rebinned. The phase lags between the two energy bands 1.8-5.1 keV and 5.1-13.1

keV are quantified by means of the cross spectral analysis. The cross spectrum is defined as $C(j) = X_1^*(j)X_2(j)$, where $X_i(j)$ is the measured complex Fourier coefficient for energy band i at a given frequency f_j. The phase lag between the signals in the two bands is given by the Fourier phase $\phi(j) = \arg[C(j)]$ (the position angle of the cross-vector C in the complex plane). The time lag in Fourier frequency f_j is constructed from $\phi(j)$ by dividing by $2\pi f_j$. The segments with data gaps as well as those outside boxes in Fig. 1 are excluded in the analysis.

The cross spectra of Cir X-1 on the different branches of the HID show that the phase lags above 60 Hz are consistent with $|\phi(j)| = \pi$. This is explained as due to the dead-time effect (van der Klis et al. 1987; Vaughan et al. 1999), which should be corrected. Thus we subtracted a cross vector averaged over 72 to 128 Hz from the average cross spectrum. The corresponding white noise is subtracted from the PDS following the model of Zhang et al. (1995).

3. Results

We compute the averaged cross spectra and PDSs for Cir X-1 when it is on the vertical HB (from box 1 to 5), on the horizontal HB (box 6-13), on the NB (box 14-20), and on the FB (box 21-24) in the HID. The results are shown in Fig. 2A-D, respectively. The positive time lags indicate that the observed hard photons (5.1-13.1 keV) lag the soft photons (1.8-5.1 keV), namely hard time lags, while the negative time lags indicate that the soft photons lag the hard photons, namely soft time lags.

Fig. 2A (upper panel) indicates that on the vertical HB, strong and narrow HBOs are present for Cir X-1. The hard time lags decrease with increasing Fourier frequency to about 40 Hz, and soft time lags appear below 0.1 Hz and above about 40 Hz [Fig. 2A (lower panel)]. On the horizontal HB, a bump near 4 Hz appears in the PDS and the centroid frequency of the HBO increases with increasing count rate [Fig. 2B (upper panel)]. On the NB, there is a wide NBO near 4 Hz in the PDS [Fig. 2C (upper panel)], and the soft time lags decrease with Fourier frequency [Fig. 2C (lower panel)]. On the FB, the PDS shows only VLFN [Fig. 2D (upper panel)], and the apparent negative time lags decrease slowly with frequency [Fig. 2D (lower panel)]. The time lags change from positive to negative when Cir X-1 evolves from the vertical HB to the FB, indicating that its cross spectrum evolves along the track in the HID.

To investigate the correlation between the source position in the HID and the characteristics of temporal variability, we introduce a parameter "S_z", which measures the position of Cir X-1 on the Z track in the HID. We set S_z of box 1, 6, 13, and 21 to -1, 0, 1, and 2, respectively (see Fig. 1). The S_z values of the other boxes are determined by linear interpolation.

In order to study the correlation between S_z and the time lag of HBO, we compute the average PDS in each box, then fit the PDS with a model composed of two Lorentzians and a power law to obtain the centroid frequency (ν_{HBO}) and the full width at half maximum ($\Delta\nu_{HBO}$, FWHM) of the HBO. The time lags are averaged over the frequency range between $\nu_{HBO} - \frac{1}{2}\Delta\nu_{HBO}$ and

$\nu_{HBO} + \frac{1}{2}\Delta\nu_{HBO}$. On the horizontal branch, the Quasi-Periodic Oscillation (QPO) fades with increasing S_z and reaches a minimum ("knee") near hard apex. So we only compute the cross spectrum from box 1 to box 11. The average time lags are approximately anti-correlated with S_z, as shown in Fig. 3 .

The NBO is present over the entire NB but is most prominently peaked at the middle. In order to study the correlation between the time lag near the NBO frequency range and S_z, we compute the average time lag in the range 2 - 6 Hz, and regard this as the time lag of the NBO. The correlation is shown in Fig. 4. It shows a negative time lag that decreases with increasing S_z.

To summarize the results from the above studies:

- The evolution of PDSs of Cir X-1 agrees with the results by Shirey et al. (1999). For example, the centroid frequencies of HBOs vary from $\sim$12 Hz to $\sim$25 Hz on the vertical HB, remain close to $\sim$30 Hz and fade into a "knee" on the horizontal HB, while those of NBOs peak at about 4 Hz.

- The cross spectra of Cir X-1 show evolution from a hard lag on the vertical HB to a soft lag on the FB (Fig. 2).

- The time lags in the HBO frequency range decrease with the centroid frequency of HBO (Fig. 3). The time lag in the HBO frequency range changes from a hard lag to a soft lag near the hard apex (Fig. 3).

- The average soft time lags between 2 Hz and 6 Hz suggest that the soft photons lag the hard ones in the NBO frequency range and the time lag shows a trend decreasing with S_z (Fig. 4).

The cross spectra of Cir X-1 we showed above are similar to them of GX 5-1 and Cyg X-2 on the HB, but are different from those on the NB (van der Klis et al. 1987; Vaughan et al. 1994). Our results also show that the time lags of the very low frequency noise (VLFN) on the FB are soft time lags.

4.   Discussion

We have analyzed the $RXTE$ data of a complete spectral track of the Z source Cir X-1 during its active phase. The time lags of the 5.1-13.1 keV photons relative to the 1.8-5.1 keV ones are measured. The cross spectra show that 5.1-13.1 keV photons lag 1.8-5.1 keV photons on the HB, and that the 1.8-5.1 keV photons lag 5.1-13.1 keV photons on both the NB and the FB. The cross spectra evolve along the track in the HID. If S_z, the position of the source at the HID, represents the mass-accretion rate of the source, the evolution of the cross spectrum along the track suggests that the cross spectrum varies with the mass-accretion rate.

Both shot profile properties and Comptonization of photons can introduce time lags. Shibazaki et al. (1988) found that energy-dependent shot profiles can produce low-energy time lags in the cross spectrum at frequencies of the shot time scale (tenth of a Hertz to a few Hertz) without noticably affecting the cross spectrum at higher frequencies. The shot model explains the cross spectrum of GX 5-1 and Cyg X-2 well (Vaughan et al. 1994). However, because of the difference between the hard lags above 0.3 Hz in the cross spectrum of Cir X-1 and those of Cyg X-2 and GX 5-1, the shot noise model may need a modification to explain the results of Cir X-1 in the sense that the shot profiles do not have an obvious evolution.

On the other hand, the Comptonization models, e.g., the uniform corona model (Payne 1980), the non-uniform corona model (Kazanas, Hua & Titarchuk 1997), and the drifting-blob model (Böttcher & Liang 1999), only explain the hard time lags (see the review by Poutanen 2000). In those Comptonization models, the photons are scattered off energetic electrons and gain energy when they go through the hot electron clouds (corona). The observed hard photons undergo more scatterings than the soft photons in the corona, therefore naturally tend to lag them. The disadvantages of these models are that they can not explain the soft lags and a static corona cannot be used to explain the evolution of the time lags.

In order to explain the observed soft lags and the evolution of the time lags of QPO in the superluminal source GRS1915+105 (Cui 1999; Reig et al. 2000), Nobili et al. (2000) proposed a Comptonization model in which the corona consists of a hot electron cloud in the inner part and a warm one in the outer part. If the optical depth of the hot plasma cloud is very large, the photons that go through the inner parts of the corona can be efficiently Comptonized and become harder. In the outer part, the hard photons escaping from the inner part are scattered by warm electrons and give away their energy, thus the soft lags would be measured.

The X-ray energy spectra below about 13 keV of Cir X-1 observed by BeppoSAX are well described by the Comptonization of soft photons (Iaria et al. (2000)). Suppose that the structure of the plasma cloud in Cir X-1 is similar to that in GRS 1915+105, the time lags observed in Cir X-1 can be explained by the Comptonization model proposed by Nobili et al. (2000).

When Cir X-1 is on the HB, the photons from the central source are upscattered by hot electrons in the corona. They gain energy and produce the positive time lags. The photons may hardly undergo downscatters in the outer part which is an optically thin corona. This leads to the hard lag. When the mass-accretion rate increases, the electrons in the inner part of the corona are cooled by the photons, resulting in a smaller radius for the inner part of corona, thus the time lag becomes smaller. Similarly, the photons contribute to the HBO may also go through the same process and show a decreasing time lag with increasing S_z (Fig. 3).

On both the NB and the FB, the plasma in the inner part become hotter and denser. This might be caused by an approximately radial inflow extending from the inner accretion disk to the compact central corona (Lamb 1988; Miller & Lamb 1992). The soft photons going through the inner part are effectively Comptonized and hardened. When they traverse to the outer cooler

plasma, they are down-scattered by electrons and give away their energy. This introduces the soft lag.

In conclusion, the time lag observed in Cir X-1 seems consistent with the Comptonization model with two layers of corona. Further study of the correlation between the Comptonization spectral component and the time lag in Cir X-1 is crucial to understanding the above interpretation.

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Fig. 1.— The HID of Cir X-1. Each point corresponds to 16 s of background subtracted data from 4 PCUs. Each box includes $\geq$1200 s data.

Fig. 2.— The PDSs (upper panels) with 1.8-5.1 keV and the cross spectra (lower panels) between 5.1-13.1 keV and 1.8-5.1 keV with 16 s segment on the vertical HB (label A), the horizontal HB (label B), the NB (label C), and the FB (label D), respectively. The data points outside the boxes in Fig. 1 or including gaps in the HID are not used. The "+" and "○" represent the hard and soft lag respectively. The time lags evolve from the positive to the negative with disappearance of HBO and appearance of NBO along the Z track. There is a negative time lag trend below 0.3 Hz in the cross spectrum of the HB.

Fig. 3.— The QPO centroid frequency (upper panel) and the time lag of QPO (lower panel) on the HB, plotted as a function of S_z, which measures the position of Cir X-1 in the HID. Results from the box 11 and 12 are excluded because the QPO of these two boxes have faded into a "knee" and a significant centroid frequency and FWHM can not been obtained. Note that a positive time delay is a hard lag.

Fig. 4.— The average time lag between 5.1-13.1 keV and 1.8-5.1 keV in the frequency range between 2 Hz and 6 Hz on the NB and at the end of the HB where a QPO around 4 Hz is observed.